average) and slow flow near the no-slip boundary. The rectangular microchannel has two axis points (lateral and transverse) with no slip boundary conditions. The resulting parabolic flow profile gives gradients in velocity in both the x and y direction. The resulting 2-D gradients give rise to the multiple slopes in the straight channel RTD.

Example 19

Vorticity in Microchannels with Surface Features

Vorticity

Vorticity (ω) is the local vector component or rotation of flow, the vector product of the del vector (∇) and the velocity vector U.

$$-\omega=\nabla\times u$$

The magnitude of this vector is proportional to the strength of the rotation of the fluid, and thus is a means to quantify the degree of mixing. It turns out that the vorticity vectors move in ways which mirror the motion of the fluid itself. If the fluid is stretched, the vorticity increases along the axis of stretching; if the fluid is tilted, the vorticity vectors tilt with it; viscosity acts on vorticity exactly as it does on velocity. The vorticity for fully developed laminar flow is theoretically zero and thus the corresponding flat channel microchannel will have zero vorticity once the flow is fully developed.

[0352] The following conditions were used for the steam methane reforming CFD simulations in microchannel with surface features for which the vorticity comparisons were made.

 [0353] 0.0125" (0.32 mm) main channel gap

 [0354] 2.5" (63.5 mm) long

[0360] Reynolds number ~1450, and well within the laminar regime.

The evaluated geometries were (all geometries had angles of 45 degrees, except the SFG-4 geometry, which had an angle of 22.5 degrees):

SFG-0F-Cis-A (SFG-0 with Fanelli)

SFG-0-Cis-A

SFG-0-Cis-B

SFG-0F-Trans

SFG-4-Trans

[0361] Using the FLUENT CFD computer code a calculation of the volume averaged overall vorticity magnitude of the full channel volume was completed, including the open channel and surface features volume. The table below shows the vorticity results and qualitative mixing results for the streams. The higher the degree of vorticity in the channel qualitatively correlates with improved mixing. The degree of mixing for a given surface feature could correlate better with the main channel vorticity or the surface feature volume vorticity. Vorticity is a function of local velocity so density and velocity can change its overall value.

[0362] A cross-section of SFG-0-Cis-A's fluid vorticity magnitude across a cross-section 1.875" down the channel showed a high degree of vorticity in the corners of the main channel. The interaction between these three surfaces in the corners and the channel flow help generate mixing in the surface features and the surface of the main channel.

TABLE

Geometry and volume-average vorticity magnitude and qualitative mixing results.

Surface Feature geometry	Volume-averaged vorticity magnitude (s^{-1})	Qualitative Mixing results
SFG-0F-Cis-A	77841	Two vortices see the cross-width centerline mix three times through the surface feature before exiting - Good mixing
SFG-0-Cis-A	75830	Two vortices see the cross-width centerline path lines mix three times through the surface feature before exiting - Good mixing
SFG-0-Cis-B	74525	Two vortices in which the cross-width centerline path lines run into the surface features centers and recirculate without leaving the surface feature
SFG-0F-Trans	72468	Two vortices with the cross-width centerline path lines sees some mixing, but the centers of each vortice don't mix much
SFG-4-Trans	71628	The whole channel's flow rotates but the center of the flow doesn't enter the surface features

[0355] 0.160" (4.1 mm) wide main channel

[0356] Surface features of 0.015" (0.38 mm) span, 0.010" (0.25 mm) depth, and 0.015" (0.38 mm) separation

[0357] 10 m/s inlet flow rate

[0358] 350 psig (25.1 bar) outlet

[0359] 3 parts steam to 1 part methane

[0363] The magnitude of the vorticity vector ranged from 100 (hz) to more than 628,000 hz. The average volume averaged vorticity for this case exceeds 70,000 hz This surprisingly high vorticity reflects the excellent degree of mixing created by surface features. It should be noted that vorticity alone is insufficient to ascribe performance for a unit operation with an active surface feature. The pattern SFG4 (trans) has a relatively high vorticity, although not as high as SFG0, but it does not provide excellent performance.